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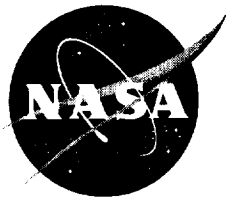

Multimodal Perception and Multicriterion Control of Nested Systems:

III. A Functional Visual Assessment Test for Human Health Maintenance and Countermeasure Evaluation

Gary E. Riccio and P. Vernon McDonald
Nascent Technologies Ltd.

Jacob Bloomberg
Lyndon B. Johnson Space Center

September 1999

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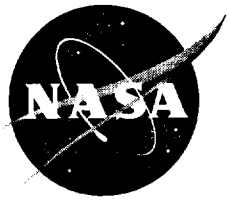

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ACRONYMS

DVA	dynamic visual acuity
FVAT	Functional Visual Assessment Test
HEDS	Human Exploration and Development of Space
IPT	Integrated Program Team
JSC	NASA Johnson Space Center
LDVA	locomotor dynamic visual acuity
MER	Medical Evaluation Requirements
NAS	National Academy of Sciences
NRC	National Research Council
SMMaC	Space Medical Monitoring and Countermeasures
SMO	Supplementary Medical Objectives
VOR	vestibuloocular response

PREFACE

This series of three reports will describe the challenges to human perception and motor control that result from whole-body perturbations during locomotion. Our approach to this set of problems is based on the assumption that individuals, in the context of their surroundings, are adaptive nonlinear control systems with multiple levels of nesting, multiple inputs, and multiple outputs. We consider interactions between individuals and their surroundings to be the fundamental units of analysis for research in human perception and movement. Our approach to the analysis of nested biological control systems was developed from over more than a decade of research on human-machine interactions in aerospace operations. The early research was conducted in collaboration with the Air Force Armstrong Laboratory at Wright-Patterson Air Force Base, Ohio (see e.g., Brown, Cardullo, McMillan, Riccio & Sinacori, 1991; Riccio, 1993b; Zacharias, Warren & Riccio, 1986). Recent research also includes collaboration with the Neuroscience Laboratory at the NASA Johnson Space Center in Houston, Texas (see e.g., Riccio, McDonald, Peters, Layne & Bloomberg, 1997).

The first report in the series, "Multimodal Perception and Multicriterion Control of Nested Systems: I. Coordination of Postural Control and Vehicular Control," describes the theoretical and operational foundations for our analysis of human-environment interactions. This report focuses on the coupled biological control systems involved in piloting an air vehicle and in stabilizing perception and movement in the cockpit. It is emphasized that the analysis is not limited to vehicular control. The analysis is presented in a way that generalizes to all forms of locomotion and to other activities that involve whole-body perturbations. In addition, the report motivates and facilitates comparisons between conditions of real and simulated vehicular motion. This provides a framework for assessing human perception and performance in real-world conditions, in controlled conditions that allow for more refined measurement and evaluation, and in simulations that are intended to foster the development of skill.

The second report in the series, "Multimodal Perception and Multicriterion Control of Nested Systems: II. Constraints on Crew Members During Space Vehicle Abort, Entry, and Landing," applies our theoretical framework for nested human-environment interactions to the problems of flight crew perception and performance during planned and potential aerodynamic maneuvers of space vehicles. This report presents an approach to the identification of task demands on perceptual and motor systems on the flight deck, to the measurement of perturbations to and interactions among the various subsystems of the human body, to the assessment of the skills involved in coordinating the nested subsystems in the presence of such disturbances, and to the development of flight deck displays and controls that promote such skill and that increase robustness of the human-machine system.

The third report in the series, "Multimodal Perception and Multicriterion Control of Nested Systems: III. A Functional Visual Assessment Test for Human Health Maintenance and Countermeasure Evaluation," applies our theoretical framework to the problem of eye-head-trunk coordination during walking or running. This report presents a method for evaluating visual resolution and gaze stability during common activities involving whole-body motion. The functional visual assessment test that is described provides a measure of visual "acuity" that is sensitive to coordination between the oculomotor subsystems and other biomechanical subsystems of the body. This approach enhances diagnostic sensitivity to a variety of physiological impairments, and it enhances diagnostic relevance with respect to operational or every-day activities.

Abstract

Our theoretical and empirical research on the whole-body coordination during locomotion led to a project conducted in collaboration with the Neuroscience Laboratory at NASA Johnson Space Center (JSC). The purpose of the project was to design an innovative system for evaluating eye-head-trunk coordination during whole-body perturbations that are characteristic of locomotion. The approach we used to satisfy the project objectives was based on a structured methodology for the development of human-systems technology. Accordingly the project was broken down into a number of tasks and sub-tasks. In sequence, the major tasks were (1) identify needs for functional assessment of visual acuity under conditions involving whole-body perturbation within the NASA Space Medical Monitoring and Countermeasures (SMMaC) program and in other related markets; (2) perform a needs analysis by evaluating the causes and symptoms of impaired visual acuity under conditions involving whole-body perturbation; (3) translate the analyzed needs into technology requirements for the functional visual assessment test (FVAT); (4) identify candidate technology solutions and implementations of FVAT; and (5) prioritization and selection of technology solutions. The work conducted in these tasks is described in this final volume of the series on multimodal perception and multicriterion control of nested systems. While prior volumes in the series focus on theoretical foundations and novel data-analytic techniques, this volume addresses technology that is necessary for minimally intrusive data collection and near-real-time data analysis and display.

1. Task 1—Needs Identification

1.1 NASA Space Medical Monitoring and Countermeasures

Under the auspices of NASA's Human Exploration and Development of Space (HEDS) Enterprise, JSC is identified as a Center of Excellence for Biomedical Research and Countermeasures. Under HEDS Goal 3: "Achieve Routine Space Travel," JSC is tasked to: "Improve and validate medical systems for crew health monitoring, intervention and care." To satisfy this goal JSC has implemented the SMMaC program. The intent is to better serve the flight crew and mission success through the provision of state-of-the-art health-monitoring procedures and countermeasure strategies. Two classes of medical monitoring were defined: the Medical Evaluation Requirements (MERs) and the Supplementary Medical Objectives (SMOs).

1.1.1 Supplementary Medical Objectives

SMOs are activities with a defined objective designed to supplement the understanding of astronaut health relative to spaceflight and/or develop associated countermeasures and prescriptions. SMOs can be ground-based or flight-based. They require voluntary participation and are crew member optional. Informed consent is required. SMOs are expected to provide rapid assessments of issues related to clinical questions. During the establishment of the SMMaC program, the "Neurological Function" Integrated Program Team (IPT)—consisting of NASA scientists, flight physicians, and outside experts—concluded that a test of dynamic visual acuity (DVA) should be included as a SMO with the intent that the test would provide a functional evaluation of crew member health in terms of visuomotor coordination. The current implementation of this SMO is the locomotor dynamic visual acuity (LDVA) test. This test was devised and implemented for the Neuroscience Laboratory at JSC with the assistance of

Nascent Technologies Limited. Baseline data from normals and labyrinthine (LD) patients can be found in Hillman et al. (in press). Flight surgeons currently use data from the LDVA to aid in deciding when to permit a "return to duty" status for flight crew following long-duration spaceflight (McGinnis, 1998).

1.1.2 Medical Evaluation Requirements

MERs are health-monitoring activities and countermeasure strategies that are medically *required* to maintain astronaut health preflight, in flight, or postflight. MERs scheduled for recent American crew on *Mir* included:

- private medical conferences
- medical therapeutics
- postflight rehabilitation
- physical exam
- medical status checks
- psychological training and monitoring
- bone densitometry
- physical fitness assessment
- tilt test
- entry monitoring
- stand test
- functional neurological assessment
- radiation biodosimetry
- crew microbiology
- photodocumentaion of skin injuries and allergic reactions
- toxicological assessment of *Mir* air
- analysis of *Mir* water
- *Mir* microbiology

Currently the functional neurological assessment MER consists of an abbreviated test based on the Equitest™ system for assessing balance control. One criterion for a test to be classified as a MER is the provision of a test-specific clinical database for comparison and determination of specific criteria for nominal performance. It is our intention that the FVAT will become an element of the functional neurological assessment MER.

1.2 Other Applications

1.2.1 NASA HEDS Research & Development

The initial motivation for the development of the FVAT was to assess the visual acuity of astronauts in a way that is as functionally relevant as possible. Crew members must function under conditions that compromise the effectiveness of the sensorimotor and musculoskeletal systems involved in stabilizing the eyes and the head (e.g., the aftereffects of prolonged spaceflight). The FVAT examines the functional consequences of such conditions on visual acuity by coupling an optometrically valid test to whole-body perturbations. Moreover, the commensurability between such perturbations and optometric specifications (i.e., relations between vibration and blur) allows for generalization from test conditions to different perturbations and different visual surroundings. Thus, the FVAT facilitates estimation of the effects of whole-body perturbations on the visibility of well-specified objects in the surroundings.

We have examined the potential consequences of aero disturbances and vehicular "vibration" on human perception and performance in a cockpit (e.g., Riccio & McDonald, 1997; McDonald, Riccio, & Bloomberg, 1997; see also Section 2). FVAT will help quantify such effects in ways that are commensurate with human engineering descriptions of the spatiotemporal characteristics of instruments and displays. This will allow human perception and performance to be evaluated or predicted for situations

that have not yet been experienced or that would not be safe to test in an actual aerospace vehicle (e.g., certain take-off abort scenarios). Information from the FVAT also can guide design modifications that enhance the robustness of cockpit instruments and displays with respect to effects of the aerospace environment on human perception and performance.

1.2.2 Biomedical Research and Training

Physiological impairments can affect DVA in ways that are similar to the effects of prolonged spaceflight. Disorders of the vestibular system, for example, can affect eye-head coordination and postural control. Postural control also is affected by neuromuscular disorders that lead to ataxia or spasticity. Tests of DVA provide valuable information on the functional consequences of such sensory and motor disorders. We believe that the value of DVA tests can be enhanced significantly by solidifying and clarifying their correspondence with extant tests of vision and motor control in medical specialties ranging from ophthalmology to neurology. A battery of complementary tests enhances diagnostic differentiation and specificity. Toward this end, it will be important to collaborate with the medical research community in the further development of the FVAT.

It is instructive to compare the effects of spaceflight on DVA with the various clinical disorders. Such comparisons can provide insight into the mechanisms that underlie normal and abnormal coordination and control of the eye, head, and torso under conditions of whole-body perturbations. For this reason, NASA scientists have sought out opportunities for collaboration with the medical research community. Scientists involved in the SMMaC program have collaborated with researchers from the Baylor College of Medicine on issues pertaining to oculomotor control and postural control, especially with respect to the role of the vestibular system. In recent years, this collaboration has focused on DVA as a measure of the functional integrity of sensorimotor subsystems. The FVAT would be a useful methodology for research on oculomotor and postural disorders. Perhaps more importantly, it would provide a face-valid method of quantifying the effects of various treatments of rehabilitative regimens.

It should be noted that the FVAT could become a valuable tool for medical education and training in various specialties. One reason for this is that it can show how isolated impairments in particular physiological systems can influence whole-body coordination and functions that are clearly relevant to the activities of daily living. In addition, the disturbance and display components of the test can be manipulated for the purpose of demonstrating to a student what impairments in DVA are like for patients with particular disorders. The reason is that DVA (i.e., output) is influenced by the spatiotemporal characteristics of perturbations (i.e., inputs) as well as by the functional integrity of compensatory physiological mechanisms (i.e., system dynamics). Understanding of the trades between inputs and system dynamics, with respect to DVA, will increase as FVAT data are accumulated on various patients and other populations. The pedagogical value of FVAT will increase accordingly.

2. Task 2—Needs Analysis: Causes of Impairments in Dynamic Visual Acuity

2.1 Research on the Effects of Spaceflight

Crew members have consistently expressed certain postflight experiences, such as oscillopsia, consistent with degraded visuomotor function. For example, the Shuttle Crew Operations Manual indicates:

> Returning from orbit, some crew members have reported increased sensitivity to g as it builds during entry. One crew member observed that "when you hit a quarter g on entry, it seems like two g's in the T-38." Crew members should be aware that their ability to perform entry tasks may be degraded from that experienced in the SMS during training. Keep in mind that G's stay around 1.3 until Mach 2.5... When returning from orbit, crew members should be aware of the potential for some change in the vestibular sensations. Head movements will tend to make these changes more noticeable. Flight crew members should avoid exaggerated head movements during landing to reduce the possibility of disorientation. (p. 7.4-24)

Recent experimental data show that stable visual performance is compromised following short- and long-duration flight (6 subjects tested within the NASA-*Mir* Program; see Bloomberg, Koslovskaya et al., 1998a,b). In ongoing investigations of gaze stability while walking on a treadmill crew members have consistently reported increased oscillopsia (movement of the visual world) following flight while fixating gaze on a target 30 cm from their eyes (Bloomberg et al., 1997). The same task also revealed changes in eye-head-trunk coordination. *Spaceflight adaptation appears to disrupt the compensatory synergy of the eye-head-trunk which together act to maintain stable gaze* under conditions of vertical trunk motion and head vibration (Bloomberg et al., 1997a).

Nascent Technologies recently participated in extending this investigation to include an evaluation of DVA following long-duration flight. This task entails walking and running on a treadmill while reading back numbers displayed on a computer screen (the LDVA test). We have clear evidence indicating that performance following flight (24 hours after landing) is decreased (Bloomberg et al., 1997b; McDonald et al., 1997b). We consider this task analogous to reading under vibratory conditions since the interaction with the support surface causes vibration of the head, especially around heel strike. Usually the body acts to attenuate this vibration. However, we have reason to believe adaptation to weightlessness also causes changes in this capacity (McDonald et al., 1996a; McDonald et al., 1997a). Our data on spaceflight-induced changes in the shock absorbing system indicate that the temporal and spectral characteristics of shock attenuation are modified immediately after flight resulting in concomitant changes in head acceleration (McDonald et al, 1996b; Lafortune et al., 1996). Our pre- and post-flight assessment of DVA testing has received favorable evaluation by crew members who participated in the testing. DVA testing has now been integrated into the SMMaC program.

2.2 Relevant Research on Whole-Body Vibration

Perturbations of the head in the vertical axes can disrupt the control of gaze and interfere with maintenance of the point of regard on an object in the near field. It is difficult to estimate the effect of perturbations when compensation by the eyes and the head is not perfect. One could use models of visual perception to estimate the effects of 'retinal slip' on the contrast (i.e., on the blur) of targets of various sizes and spatial detail. Such estimates are not trivial and they are dependent on the precision

with which eye movements are measured. It is difficult, if not impossible at present, to measure eye movements with the requisite accuracy without influencing the eye movements themselves. Another approach is to measure visual performance, with psychophysical methods, under different conditions of perturbation (Boff & Lincoln, 1988; Griffin & Lewis, 1978; Moseley & Griffin, 1986; see Figures 1-6). Such research on vibration and display perception provides an experimental paradigm that can be adapted to assess the functional efficacy of postural skills with respect to visual tasks that are characteristic of aerospace operations or the skills of daily living (Riccio & McDonald, 1998; McDonald, Riccio, & Bloomberg, 1998).

Psychophysical experiments reveal that visual performance (e.g., reading a numeric display) is affected by vertical "vibration" of the observer (Boff & Lincoln, 1988; Griffin & Lewis, 1978; Moseley & Griffin, 1986; see Figures 2-5). Effects of vertical perturbations on visual performance are greater when the task requires maintenance of the point of regard on an object in the near field than when the task simply requires maintenance of the direction of gaze (Moseley & Griffin, 1986; Wilson, 1974). The effects of vertical perturbations on visual performance are influenced directly by the size and contrast of the task-relevant optical detail as in any visual acuity task (Furness, 1981; Lewis & Griffin, 1979). The magnitude and frequency of the perturbations also influence effects. Significant impairments in visual performance have been observed at vertical accelerations as low as 0.25 g and for frequencies of vibrations below 10 Hz (Moseley & Griffin, 1986). These magnitudes and frequencies are in the range of postural perturbations during walking. Effects on visual performance are greater for combined horizontal and vertical perturbations than for vertical alone (Meddick & Griffin 1976).

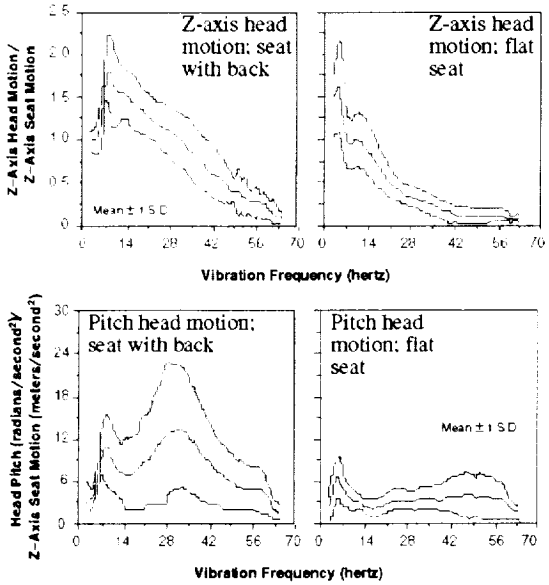
2.3 Relevant Research in Ophthalmology and Neurology

The LDVA test, currently in use in SMMaC, was evaluated in a test of normal and labyrinthine deficient (LD) patients (Hillman, et al., 1999) in a collaborative effort between representatives of Nascent Technologies, Baylor College of Medicine, and the Neuroscience Laboratory at JSC. This investigation demonstrated that the LDVA test was repeatable across test session, and consistent when used in different testing locations. Moreover, the test clearly discriminated the LDs from the normal test subjects.

In a similar collaborative effort, an investigation was performed to determine the influence of vestibuloocular response (VOR) gain on performance on the LDVA test. Subjects had their VOR gain adapted by fixating gaze while performing continuous yaw head rotations, and while wearing 0.5 minifying lenses. On average VOR gain changed about 10%, and LDVA performance data indicated a small, but significant decrement in LDVA performance (Merkle and Bloomberg, 1999).

Dr. Helen Cohen of the Baylor College of Medicine and the National Space Biomedical Research Institute is currently using the LDVA as a bedside evaluation of patients following acoustic neuroma resection. The intent of this evaluation was twofold: to determine the sensitivity of the LDVA for tracking recovery of function following the procedure, and to use the LDVA as a measure of the effectiveness of the rehabilitation regimen utilized with these patients. Preliminary data indicate the LDVA to show recovery of function over an initial 5-day post-operative period (Bloomberg, Mulavara, et al., 1998). Evaluations of the patients further into recovery are being collected.

Figure 1. Transmissibility as a function of vibration frequency. Center curve is mean vibration amplitude; top and bottom curves are ±1 standard deviation. (From Boff & Lincoln, 1988).



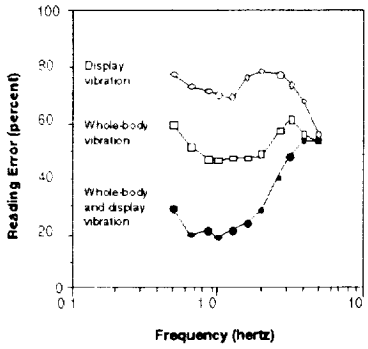


Figure 3. Reading error for three display viewing conditions, 0.5-5 Hz. (From Boff & Lincoln, 1988).

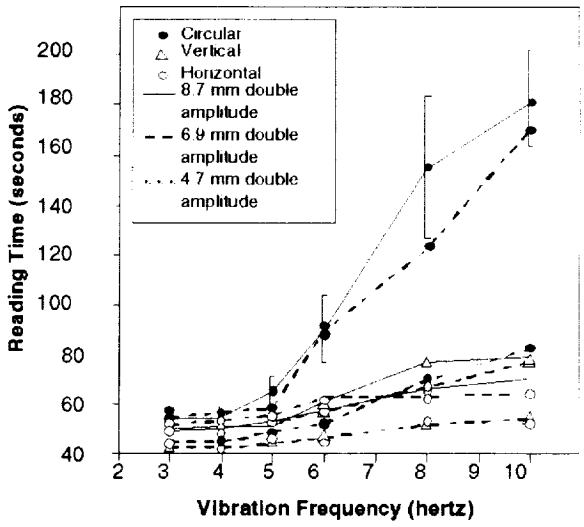


Figure 2. Effect of vertical, horizontal, and dual axis (circular) vibration on visual performance. (From Boff & Lincoln, 1988)

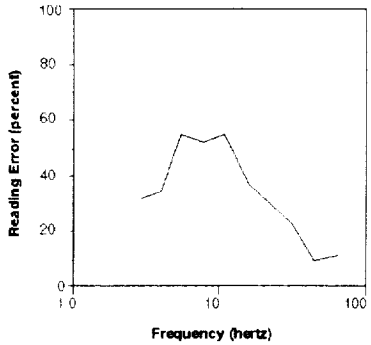


Figure 4. Reading error: whole-body vibration, 2.8-63 Hz. (From Boff & Lincoln, 1988).

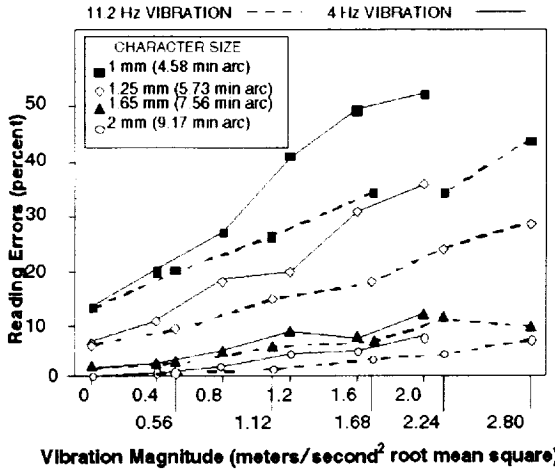


Figure 5. Increase in mean reading error with vibration magnitude for four character sizes. (From Boff & Lincoln, 1988).

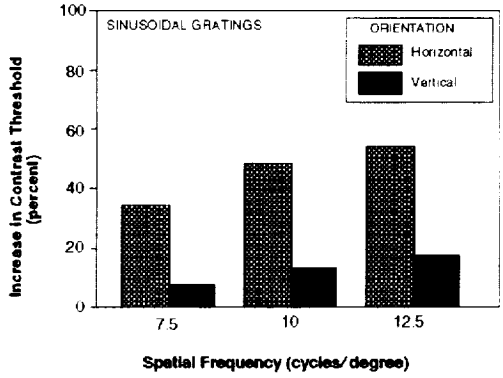


Figure 6. Effect of whole-body vertical vibration on contrast threshold for sinusoidal gratings with spatial frequencies of 7.5, 10, and 12.5 cycles/deg. (From Boff & Lincoln, 1988).

NASA Flight Surgeons have used the LDVA test in case studies of NASA pilots complaining of suspected vestibularly mediated problems. These tests were performed in collaboration with the Neuroscience Lab at JSC, and data were used to supplement the standard neurological screening performed by the NASA Flight Surgeon.

3. Task 3—Biobehavioral Engineering Translation

3.1 Apparatus and Facility Requirements

3.1.1 Displays and Viewing Conditions

The display to perform a test of dynamic visual acuity must possess sufficient resolution and appropriate brightness/contrast specifications, and be readily available at a reasonable cost. Viewing conditions must be controlled in order to minimize glare, attain a consistent level of ambient illumination, and eliminate any distractions in the visual field. In addition the viewing distance, angle, and display location/orientation should be consistent with optometric standards. The following guidelines are based on the "Recommended Standard Procedures for the Clinical Measurement and Specification of Visual Acuity" produced by Working Group 39 of the National Academy of Sciences (NAS)-National Research Council (NRC) Committee on Vision (NAS-NRC, 1980).

(1) The test display should be placed at a distance of 4 m because (a) significant accommodation does not come into play, (b) acuity is maximal and dispersion of acuity scores is minimal, (c) use of the metric system is more universal, (c) it is simpler to convert Snellen Fractions for a 20-ft distance to their equivalents at 4 m than for a 6-m distance, and (d) there are limitations on available space in most testing facilities.

(2) The test display should be comprised of black figure(s) centered on a white background with a contrast of not less than 0.85 (defined as the difference between the figure and the background luminances divided by the background luminance). The luminance of the white background should be approximately 85 cd/m^2. The background should extend at least 1 deg beyond the figure in order to minimize "contour interaction."

(3) The walls, floor, and ceiling of the test room may be left in darkness or may be illuminated to produce a surround luminance preferably not exceeding one half the luminance of the display. The general illumination should not be allowed to reduce the contrast of the figure below 0.85 as a result of ambient or veiling illumination, and provision should be made for controlling general room illumination independently of the display luminance.

(4) It would be desirable to specify or control the size of the pupil during measurement of visual acuity because it influences visual resolution and blur. This is rarely practical, however, in common testing situations. Controlling the luminance in the field of view of the two eyes can minimize all but individual differences. Individual differences can be controlled analytically by comparing results from different tests (e.g., static and DVA) under comparable conditions.

(5) The wavelength composition (i.e., color) of the luminance in the field of view also can affect visual resolution and blur. Displays and sources of illumination are satisfactory if the spectral centroid (i.e., monochromatic light of equivalent hue) falls in the range between 555 and 575 nm.

3.1.2 Photometric Calibrations

Calibration will be necessary to ensure that display contrast, display luminance, and ambient luminance are within specifications. Standard methods for measurement of luminance and contrast are described in Boff & Lincoln (1988) and NAS-NRC (1980). Suitable devices (e.g., photometers, micro-photometers) and procedures should be made available to users of the optometric test so that calibration can be conducted periodically. Automatic calibration is desirable but not necessary.

3.1.3 Self-Generated Motion

Some tests of visual acuity require that the observer's head is fixed or that movement is otherwise constrained by optical devices which require precise positioning of the eye relative to external lenses and apertures. We require a test that allows for movement of the observer and, thus, a moving point of observation. In the simplest use of the test, whole-body perturbations can be produced by the observer. We have examined how DVA is affected by activities such as running in place, and hopping in place. The effects are salient. This suggests that a test of DVA could be useful even if administered in this minimalistic mode. The disadvantage of self-generated motion is that the test administrator has little or no control over the timing and magnitude of the resulting whole-body perturbations, and the perturbations are predictable.

One method to provide some test control over self-generated perturbations is to measure and provide feedback about the kinematics of the head or torso or about the kinetics of interaction with the support surface. On the basis of such feedback, the test administrator can instruct the subject to change characteristics of the activity (e.g., speed, forcefulness) until criterion levels are achieved. Test displays can be linked automatically or manually to criteria for the perturbations. If feedback is obtained in near real time, administration of the FVAT could become very efficient. The test administrator, for example, could be certain that the subject is not relying on relatively quiescent periods that are predictable within a self-generated activity. It is highly recommended that further development of the FVAT address coupling between the perturbations and displays by allowing the former to "trigger" the latter.

Feedback need not be obtained in real time for implementation of this method. Use of delayed feedback would be useful for instructing the subject about the self-generated perturbations. In this case, presentation of the test display would assume that the subject maintains the criterion level of activity during the presentation. Use of subject's response for a particular display then would depend on feedback about whether the criterion levels in fact had been maintained during the presentation. While this would not be the most efficient way to administer the FVAT, it would be sufficient for users who are not able to employ a more sophisticated version of the test.

3.1.4 Treadmill Locomotion

The evaluation of DVA during treadmill locomotion has been the principal context for use of our first-generation test of DVA (see Sections 2.1 and 2.3). This context acts as a functionally face-valid test of DVA, and therefore has potential use in simple screening protocols. Use of a treadmill provides the test administrator with more control over the whole-body perturbations than does running or hopping in place. It allows the results from the FVAT to be compared across individuals with respect to particular *speeds of locomotion.* Such comparisons could be useful in evaluation of a variety of operational

scenarios. A particular speed of locomotion can have different consequences, however, for different individuals due to such body characteristics as weight, anthropometry, and locomotor mechanics. Thus, individual differences in DVA could be obtained even if there were no differences in postural control or oculomotor control.

Diagnostically, it probably is more useful to compare individuals with respect to spatiotemporal characteristics of the perturbation. For this reason, it is highly recommended that the FVAT include feedback to the test administrator about the kinematics or kinetics of the whole-body perturbations. The advantages of incorporating such feedback into the FVAT are the same with a treadmill as they are for running or hopping in place (see Section 3.1.3). If feasible for particular users, treadmill locomotion would be preferable to running or hopping in place because the characteristics of the perturbation can be controlled more directly by the test administrator (i.e., via treadmill speed). Even if a treadmill is available, however, completely self-generated activities may be indicated for certain situations or subject populations in which postural control is severely impaired. Therefore, it is highly recommended that methods of feedback and of coupling displays to perturbations should be designed so that they can be used with treadmills and other sources of perturbation.

3.1.5 NASA Safety Requirements

In order to permit the use of the FVAT in NASA space medicine applications, NASA safety specifications will be met in all design aspects of the FVAT. IPT representatives from JSC will provide guidance on this issue. We believe that attaining full subject compliance and participation will be much easier with a dynamic seat than with treadmills or completely self-generated motion.

3.2 Test Administration

3.2.1 Relationship Between Display and Perturbations

As indicated in Section 3.1, the efficiency of the FVAT could be increased if displays and perturbations are directly or indirectly coupled. Direct coupling involves triggering a display presentation on the basis of (a) feedback about perturbation of the observer, (b) a priori information about the timing of an imposed disturbance, or (c) both. Indirect coupling involves changes in the perturbation based on information about a preceding pattern of perturbations. Changes in the perturbation could be induced by instructions to the observer who is generating the activity, or by changing a disturbance that is imposed on a moving or stationary observer. These forms of coupling would minimize the likelihood of display presentations during relatively quiescent periods (i.e., more static than dynamic). Fewer presentations would be required under these conditions to achieve a given level of test sensitivity to the functional efficacy of oculomotor and postural control systems.

3.2.2 Constraints on Subjects/Patients

The FVAT allows for use with individuals who have significant impairments in the sensorimotor or musculoskeletal systems involved in postural control and with individuals who otherwise have severe limitation in coordination, strength or stamina. We believe utilizing a dynamic seat to supply controlled perturbations will be the most generally useful version of the FVAT in this regard. Other methods of perturbation may be indicated in some applications of FVAT. Thus, the various versions of the FVAT

and the associated methods of perturbation should be designed to maximize accessibility, comfort, and safety.

Consideration also should be given to the responses required of the subject. As in the most common optometric tests, the FVAT has required verbal responses indicating identification or recognition of particular display elements. This can be a problem for subjects who are illiterate or who are not familiar with the names of elements used in the display. Letters of the alphabet were avoided in early versions of the FVAT because they would not necessarily be familiar to cosmonauts or because there was a greater likelihood of miscommunication between subject and test administrator. Some tests use orientation of display elements (e.g., the open side of an "E") to avoid this problem; however, the responses can be problematic for subjects who may confuse left-right or up-down (NAS-NRC, 1980). This is the case for subjects after long-duration spaceflight. It also is a common problem with young children, and it can be a problem for some adults.

Numbers have been used in early versions of the FVAT, but they are not desirable from the perspective of optometric standardization (see Section 3.3.1). We prefer responses that are based on orientation of optometrically standard display elements (optotypes). Orientation responses that depend on juxtaposition can avoid the problem of misorientation. In this method, a set of familiar objects can be arranged around the display as a frame. The familiar objects could be canonical positions of the hands of a clock and/or patches of colors that don't require fine spatial resolution for identification. The subject would be required to indicate which clock position or color, for example, is consistent with the orientation of the optotype. An advantage of such responses is that the response set can be small and continuously apparent. Thus, the subject is not required to cognitively search a large response set (e.g., letters of the alphabet) or to remember a small test-specific set of items. Small continuously visible response sets thus minimize response time. They also reduce the likelihood of misnaming (i.e., thinking one thing and saying another) and reduce the likelihood of multiple responses (e.g., due to nonoptimal similarity relations within the set).

3.2.3 Constraints on Test Administrators

In the NASA postflight testing there are many demands on the crew members, and in the first 24 hours the rate of recovery of function is rapid. Therefore testing must be accomplished in as short a time as possible. A time of 10 minutes has been indicated as nominal for the MER candidate evaluations. In many commercial markets the test administration must be completed in as short a time as possible. The test, as a whole, should be designed to minimize the time required of subjects/patients. In the administration of the test, there are tradeoffs between the amount of time required of the subject and the precision of the test results. Such tradeoffs are not unusual in medical diagnosis and in operational settings. More generally, they are similar to the cost-benefit analysis that is implicit or explicit in diagnostic decision making. In this context, it would be beneficial if the FVAT could be designed as a step-wise or hierarchical process. As in diagnostic decision making, in general, there is no reason to conduct the most sophisticated or sensitive tests if they are contraindicated by simpler, less intrusive, less time-consuming, or less costly tests (see Section 3.5.4).

The conditions in which the test is administered and capabilities of the test administrator should be expected to vary considerably. Test administrators may have to operate under a lot of pressure (e.g., only one opportunity to do the test) or under high workload (e.g., time pressure or other responsibilities).

Consequently the test should be as robust as possible to human error. Communication between subject and test administrator, and recording of responses, can be facilitated by the design of a suitable response set (see Section 3.2.4) and by providing sufficient time between optotype presentations. It also is recommended that the test include provisions for double-checking responses by the subject and entries by the test administrator.

3.2.4 Constraints on Use of Test Results

The test administrator should not be required to engage in protracted interpretation of abstract results. Results should be presented in a form that is familiar to the most likely users of the FVAT. The results can be presented, for example, in a form that is commensurate with optometric standards (e.g., Snellen Fractions). In this way, the effects of whole-body perturbations on visual acuity can be interpreted as blurring of the retinal image analogous to that produced by optometrically equivalent refraction errors. Snellen Fractions are useful in optometry because they interpreted readily in terms of the corrective refraction that can be provided by prescription lenses. While impairments in DVA cannot be corrected with lenses, the comparisons to refraction error are no less useful. Many operational situations and regulated activities use the magnitude and nature of refraction error as a criterion for qualification and also for remediation that enables an individual to avoid disqualification. It is recommended that FVAT results include the use of Snellen Fractions.

The FVAT result should not be limited to Snellen Fractions. Some users will need more sophisticated results, and all users are not required to use all the results that can be obtained with the FVAT. As in ophthalmology, for example, it may be necessary to use multiple tests to identify potential causes of impaired visual acuity other than refraction error (see Section 3.5.4). Impairments specific to DVA will require information about the perturbation of the head. Information that is relevant to the efficacy of oculomotor control would be provided by visual acuity results as a function of head perturbation characteristics. Information about efficacy of postural control would be provided by head perturbation data in relation to movements of the platform (e.g., feet, treadmill, or seat). Results concerning oculomotor and postural control should be presented in a form that is commensurate with standards and practices in the relevant specialties.

3.3 Optical Test Materials

3.3.1 Characteristics of Optotypes

The visual displays and display elements used in the FVAT should be consistent with optometric standards. The following guidelines are based on the "Recommended Standard Procedures for the Clinical Measurement and Specification of Visual Acuity" produced by Working Group 39 of the NAS-NRC Committee on Vision (NAS-NRC, 1980).

(1) The Landolt broken circle (ring) has been adopted as the reference standard. The critical detail in the Landolt ring (also known as the Landolt C) is the gap in the ring. The size of the gap must be 1/5 the diameter of the ring. Four separate optotype orientations are to be used for the standard test, namely with the gap up, down, right, and left.

(2) Use of the Landolt ring offers several advantages for the reference standard. It lends itself to a forced choice response (see Section 3.2.2). The four positions are produced by rotating the target around a fixed point. This minimizes artifacts and secondary cues. For a (moving) eye that yields a radially uniform image of a point, the relation to blur is the same for all positions of the Landolt ring. The Landolt ring makes proper allowances for astigmatic refraction errors and other types of anisotropic blur. It has already been widely used for assessing impaired vision and performance on tasks.

(3) The acceptability of other optotypes requires a demonstrable equivalence to the Landolt rings in terms of acuity scores (see Section 3.5.2).

(4) The variation in optotype size is approximately equal steps of 0.1 on a logarithmic scale, that is, every successively larger size is about 1.26 times the preceding one. The optotypes are to be black on a white background with a contrast of no less than 0.85. The center-to-center spacing when more than one optotype is present in a display must not be less than twice the corresponding (collinear) dimension of the optotype. In the interest of uniformity, an upper limit to the spacing that is equal to twice the specified lower limit is also suggested.

3.3.2 Isotropic Blur

This is the simplest and most common variation in static visual acuity. It results from an inappropriate accommodation, that is, a focal length for the lens of the eye that is inappropriate with respect to the distance of an object of regard. Isotropic blur probably is relatively uncommon in DVA because perturbations of the head are not necessarily equal in all directions in the frontal plane and because compensatory eye movements may not be equally efficacious in all directions. The set of optotypes should allow the FVAT to distinguish between isotropic blur and anisotropic blur. Combined with data on multi-axis perturbations of the head, results for various optotype orientations can provide insight into relative roles of postural control and oculomotor control in (impaired) DVA.

3.3.3 Anisotropic Blur

As indicated above, meridional variations in blur are probably the rule rather than the exception in DVA. Across the entire set of optotypes used in the FVAT, overall results should be not be influenced by such meridional variations. For example, the percentage of optotypes in the entire set that can be correctly identified by an observer with a particular magnitude of horizontal blur should be the same as that identified by another observer with the same magnitude of vertical blur. Otherwise the functional assessment of DVA would depend on the orientation of the observer's anisotropic blur. In the case of the Landolt rings, this can be avoided if an equal number of gap locations are included in the entire set (See Figures 7 and 8 for an example of anisotropic blur on the Landolt rings, and a close variant.). Analysis of results for particular gap locations would allow for further diagnostic differentiation between isotropic blur and anisotropic blur. This is common practice in examination of static visual acuity that differentiates between radially symmetric refraction errors and astigmatism.

3.3.4 Asymmetrical Blur

In optometry, the emphasis is on radially symmetric refraction errors and astigmatism because these problems with static visual acuity can be corrected with a combination of spherical and cylindrical

lenses. The Landolt ring test is sufficient to guide such remediation. Irregular astigmatism can result from various ophthalmic disorders. Treatments for such irregularities may require additional or more elaborate tests (NAS-NRC, 1980). The principal causes of impairments in DVA that are comparable to irregular astigmatism are postural asymmetries and hysteresis in transmission of disturbances to the head. An initial upward perturbation of the head, for example, could be larger or more vigorous than the following downward perturbation. Depending on the displacement-velocity-acceleration profiles of the opposing perturbations, such asymmetries could be exacerbated by the dynamics of the oculomotor system. Diagnostic differentiation between asymmetrical blur and symmetrical blur could help identify the causes of impairments in DVA. This could assist in developing methods for remediation (e.g., physical therapy) and in assessing the efficacy of such methods. It would be useful to develop a supplementary set of optotypes for the FVAT that provides the capability to differentiate between asymmetrical blur and symmetrical blur.

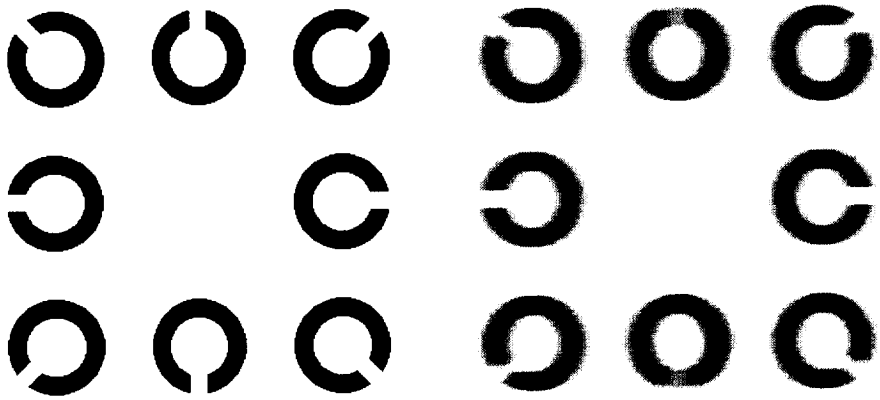


Figure 7. The effect of single-axis vibration, and the resulting anisotropic blur, on a set of Landolt rings.

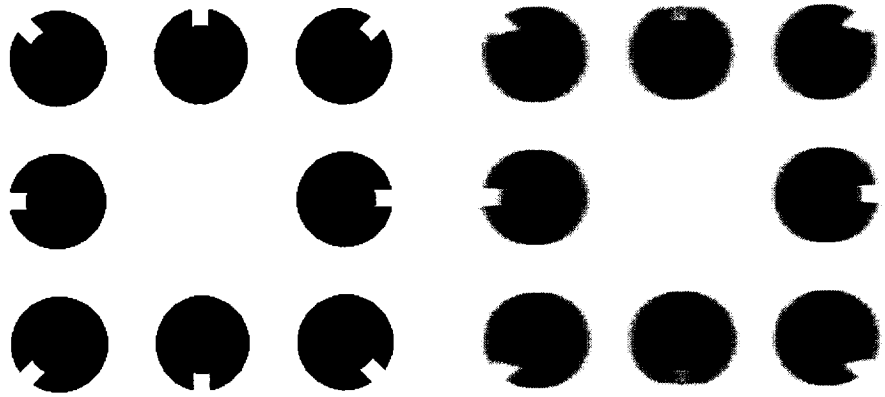


Figure 8. The effect of single-axis vibration, and the resulting anisotropic blur, on a simple variant of the Landolt rings that are readily commensurable with this primary optometric standard. The use of these optotypes would be indicated for a supplementary test to identify effects of asymmetrical blur.

3.4 Test Data

3.4.1 Visual Recognition

The data obtained with the FVAT should be consistent with optometric standards. The following guidelines are based on the "Recommended Standard Procedures for the Clinical Measurement and Specification of Visual Acuity" produced by Working Group 39 of the NAS-NRC Committee on Vision (NAS-NRC, 1980).

(1) The data must be corrected for the number of correct responses obtainable by chance. Threshold performance is defined as the level halfway between chance and 100%. Thus, for four positions of the gap in the Landolt ring, 25% can be obtained by random guessing. The 50% level is then halfway between 25% and 100%, or 63.5%.

(2) The resolution threshold occurs when the size of the optotype is reduced to the level at which a specified critical detail is just visible. In the case of the Landolt rings, the critical detail is the gap in the ring. The size of the gap is specified in minutes of arc. This is known as the visual angle method of specifying the size of optotypes and the resolution threshold.

(3) Visual acuity is the reciprocal of the resolution threshold when it is expressed in terms of critical detail size in minutes. Visual acuity can be expressed as a Snellen fraction in which the numerator is the actual distance of the test chart and the denominator is a measure of the relative size of the optotype defined as the distance at which the critical detail of the Landolt ring subtends 1 min. It is recommended that the Snellen fraction be expressed in metric units (i.e., meters).

(4) The reciprocal of the Snellen fraction (i.e., the relative size divided by distance) is numerically equal to the visual angle in minutes subtended by the critical detail (e.g., gap in the Landolt ring). Thus 4/4 and 6/6 corresponds to a visual angle of 1 min at distances of 4 m and 6 m (approx. 20 ft), respectively, while 4/8 and 6/12 refer to a visual angle of 2 min at those distances. Conversion of the Snellen fraction to its equivalent in the visual angle facilitates comparison of measures made at different distances.

3.4.2 Stability of Gaze and Point of Regard

It would be useful to have information about the proximate cause of blur in DVA, that is, about instability in the point of regard. Information about the direction of gaze is not as useful as information about the point of regard is in the assessment of DVA. The point of regard can be unstable when the direction of gaze is stable if there is translatory motion of the head in the frontal plane. In addition, the point of regard can be stable when the direction of gaze is unstable in the presence of such head motion. While information about the point of regard would be useful in the assessment of oculomotor control, it is important to note that it is not necessary in the FVAT. The efficacy of oculomotor control can be assessed in the FVAT by comparing dynamic and static acuity (i.e., with and without perturbations), by measuring head motion, and by analyzing results obtained for standard subsets of optotypes. Impaired visual resolution in a dynamic test relative to a static test can be interpreted as imperfect ocular compensation if the sizes and orientations of unresolvable Landolt gaps are consistent with the size and orientation of the observed perturbations of the head. A more detailed understanding of oculomotor control can be obtained in optometrically equivalent supplementary tests over which the spatiotemporal characteristics of head perturbations are manipulated.

3.4.3 Stability of Head Position and Motion

An important attribute of the FVAT will be the information obtained about perturbations of the head during performance of the optometric test. These data will provide the capability to differentiate between the relative roles of oculomotor control and postural control in DVA. Oculomotor control can be assessed indirectly by comparing optometric data and head-perturbation data (see e.g., 3.4.2).

3.4.4 Postural Stability

Postural control is an important component of DVA. Impaired acuity under dynamic conditions could be due, in part, to inadequate attenuation of disturbance transmission between the platform and the head. Impaired acuity also could result, in part, from lack of coordination of head-neck control with respect to movements of the torso. Ultimately, impaired acuity could be attributed to inadequate oculomotor compensation for head perturbations (i.e., proximate cause). Nevertheless, control of the head and body is important to consider because such control can reduce the demands on oculomotor compensation. It would be just as reasonable, and perhaps easier, to address postural control in a method of remediation as it would be to address oculomotor control.

Postural control can be assessed directly by comparing head-perturbation data either to data on motion of other body segments or to data on platform motion. We have developed methods for measuring perturbations of the head and torso that relate to stability and functionality of postural control (Riccio, 1993; Riccio et al., 1993; Riccio & McDonald, 1998). These methods will be incorporated into the FVAT so that they can be employed under any methods of perturbation (see Section 3.1).

3.5 Interpretation of Results

3.5.1 Psychophysics

The analysis of FVAT data should be consistent with optometric standards. The following guidelines are based on the "Recommended Standard Procedures for the Clinical Measurement and Specification of Visual Acuity" produced by Working Group 39 of the NAS-NRC Committee on Vision (NAS-NRC, 1980).

> (1) It is customary to plot the frequency of seeing data as a function of log size and to fit the data with the integral of the probability curve. There are several well-known methods of fitting such a curve to the data. It is usually assumed that when the data are corrected for guessing, 50% seeing represents the threshold. The raw data can be plotted in the form of a graph with fraction of optotypes reported correctly as a function of log size. The data in the middle of the range can be fitted with a straight line to locate the size corresponding to a particular criterion score.
>
> (2) The Committee discussed the complications involved in recognizing optotypes. In particular, when a given optotype looks like one of the remaining optotypes more than any of the others in the response set, the final choice is between the two that look most alike and the decision is not simply a matter of guessing which one out of the entire set is the correct choice. The relative confusability of the optotypes will depend not only on the optotypes in the response set but also on the meridional variations in blur. [The Landolt rings are a good response set, in this sense, because the similarity relations within the set are relatively simple and because the effects of meridional variations also are relatively simple.]

(3) There has been considerable reservation about the use of the concept of a threshold for designating the border between seeing and no seeing, because it is difficult to relate the decision about the identification of an optotype to a definite and certain introspective experience of its having been identified by a specific visual cue. Nevertheless the concept of a threshold can hardly lead to any confusion in relating scores on the visual acuity test to refractive errors and other visual impairments and to performance on the task. The Working Group has agreed to use the threshold concept as a tool for exposition and communication.

(4) The Working Group has agreed to use a correct report of 7 optotypes out of 10 as the desired criterion for assessing visual acuity. It may be noted that a raw score of 7 out of 10 yields a frequency of seeing somewhat higher than 50% [and significantly higher than the resolution threshold defined for response sets as small as 4 (e.g., with the canonical set of Landolt rings)]. With 10 optotypes, the chance of getting 7 out of 10 correct by guessing is less than 0.1% and hence such a measure of visual acuity is significant by a highly strict statistical criterion.

3.5.2 Relationships With Optometric Tests

The results from the FVAT should be commensurate with other common tests of visual acuity. The following guidelines are based on the "Recommended Standard Procedures for the Clinical Measurement and Specification of Visual Acuity" produced by Working Group 39 of the NAS-NRC Committee on Vision (NAS-NRC, 1980).

(1) The specific need for standards will vary with the type of use to which the test is put. Results may need to be compared with those attained in a previous examination. When a patient is referred from one practitioner to another, the results of the two examinations should be comparable. Standard tests are required to make such comparisons meaningful. In special situations the use of test conditions other than the standard may be required.

(2) The assessment of equivalence, between the primary standard (Landolt rings) and other optotypes, must be based on measurements made with ten different subjects who are emmetropic or corrected for ametropia and free of any clinical defect which might prevent normal vision. The ten subjects shall be a total sample, not a group of ten subjects selected from a larger sample in terms of their individual mean acuities and slopes to fulfill these criteria.

(3) In the assessment of equivalence to Landolt rings, the optotypes of a given size are to be presented one at a time at the center of a 15-deg field which has a dark surround. The order of optotypes in the sequence must be random. For each subject and for each size the total number of exposures will include 100 or more separate presentations and an equal number for each optotype. The length of the exposure is 1 sec and the interval between exposures is at least 4 sec. A warning sound will precede each exposure by 0.5 sec.

(4) The subject is to be made familiar with the optotypes to be presented. At the end of each exposure he reports what he sees or guesses to have been exposed. The subject is asked to guess if he cannot see. If the warning signal for the next presentation occurs before he responds to the previously exposed optotype, the subject must disregard the previous exposure and concentrate on the next. Failure to respond is to be recorded as an error.

(5) The procedure must be repeated for optotypes of enough different sizes to be able to plot a curve of frequency of seeing vs. log size. The whole procedure is to be carried out with a +1.00 sphere, a +1.00 cylinder x 180 deg, a +1.00 cylinder x 90 deg, and a +1.00 cylinder x

45 deg, added successively to the full correction. These latter tests enable one to assess observer performance in the presence of a modest amount of blur.

(6) After the results have been corrected for chance they must be plotted to form a frequency of seeing curve. This curve must then be analyzed to determine the size at which seeing is 50% above chance and also the slope of the curve at its midpoint. The data for ten subjects must be averaged. The means must fall within 5% of the means for Landolt rings. The slopes must be equal to or greater than the slopes for Landolt rings. This must apply to at least 40% of the subjects for each of the specified testing conditions.

3.5.3 Relationships With Non-Optometric Tests

The results from the FVAT should be commensurate with standards and practices for assessment of postural control. The methods we have developed for measuring perturbations of the head and torso (Riccio, 1993; Riccio et al., 1993; Riccio & McDonald, 1998) are consistent with methods commonly used in clinical and scientific laboratories.

3.5.4 Hierarchical Decision-Making

The FVAT should be organized into a sequence of tests that provide increasingly detailed information relevant to impairments in visual acuity. Each test could provide the basis for the decision about whether to conduct a subsequent test. This strategy, which is common in medical diagnosis, would minimize the likelihood that unnecessary tests would be administered and would minimize the time required of subjects/patients. For example, a basic test of DVA could be administered first. If no impairments in visual acuity were revealed, then there would be no reason to conduct further testing. If, on the other hand, impairments were revealed, then a comparable optometric test could be administered under static conditions. If differences between these two tests were within a nominal range, it would suggest that the impairment noted in the initial test was not due to anything peculiar to DVA. If, however, important differences were obtained between the static and dynamic tests, further assessment of DVA would be warranted. At this point, further assessment could involve analysis of the head perturbation and postural control data (see Sections 3.4.2-3.4.4). It also could involve further testing with an optotype set that focuses on particular anisotropies or asymmetries (see Sections 3.3.3-3.3.4).

4. Task 4—Technology Identification

4.1 Moving Support Surfaces

4.1.1 Treadmills

Motorized treadmills (Quinton™ Series Q55 at JSC and Quinton™ Clubtrack at Baylor College of Medicine) have been used for astronaut, patient, and normal testing. An important consideration is a large belt surface area (the Q55 has a surface area of 51 cm x 140 cm), and a stable base of support to avoid impact induced oscillations of the treadmill.

4.1.2 Posturography Platforms

We have detailed familiarity with moving platform posturography (e.g., Riccio, 1988; Riccio, et al., 1993). Consequently, we're aware of systems and methods of imposing precisely controlled disturbances on a standing subject. The best examples of such systems are those manufactured by NeuroCom International of Clackimas, Oregon. We do not plan to develop the FVAT for commercialization with products such as NeuroCom's Equitest™ System, at least not initially. Nevertheless we believe that it will be valuable to consider our motion-base systems in the context of perturbations and paradigms that are employed with such systems. One reason is the FVAT could easily be developed for use with such systems. Another reason that is more important in the near term is that the Equitest System currently is part of the functional neurological assessment MER which is the target application of the FVAT (see Section 1.1).

4.2 Optometric Tests

4.2.1 Standard Optometric Tests

A wide variety of optometric tests are described in Boff & Lincoln (1988) and NAS-NRC (1980). Most of these tests involve the use of optotypes (e.g., letters, numbers, rings, bars, gratings, checkerboards) that can easily be reproduced on a computer monitor. In Section 3, we emphasize the importance of optotypes that are commensurate with the primary optometric standard, the Landolt rings. In this regard, is it noteworthy that there is a computerized optometric test developed for the MacIntosh that uses Landolt rings (Bach, 1996).

4.2.2 Extant Tests of Dynamic Visual Acuity

DVA is that acuity attained during relative motion of either the observer or the optotypes used to measure visual acuity (Miller & Ludvigh, 1962). DVA has been measured in patients in several ways, including manually moving a display in front of a patient (Longridge & Mallinson, 1984), having a patient make active sinusoidal head movements or having a patient walk in place while attempting to read a visual display (Grossman & Leigh, 1990).

Historically the testing of static visual acuity has been well defined. Subjects read or deciphered letters, numbers, or images of a known size at a given distance. To test DVA, however, optotype motion or subject motion must be added to the testing paradigm. The earliest tests of DVA involved moving Snellen letters or Landolt C's in the horizontal plane while a stationary subject attempted to read or decipher the moving images (Ludvigh, 1948). Since those early experiments the methods of introducing movement have become more sophisticated. They now use equipment such as slide projectors and rotating mirrors to project moving images on a screen (Long & Crambert, 1990). Other early DVA studies moved the observer rather than the optotype (Miller, 1958). Miller tested DVA while rotating subjects in the horizontal plane using a motorized Link trainer. This strategy is still employed today, using modern rotator chairs to move subjects in either the vertical or horizontal plane while they attempt to read a stationary display (Demer & Amjadi, 1993). Other investigators have tested DVA while subjects made active sinusoidal head motions in the horizontal plane (Bhansali et al., 1993).

Although these tests accurately assess the vestibular and visual contributions to the maintenance of DVA, they do not address the issue of DVA during actual locomotion. Instead, these tests are usually performed under limited, controlled conditions, rather than during self-generated, goal-directed head and body movements. *To understand the functional limitations caused by impairments in sensorimotor function, however, data must be collected during performance of naturally occurring behavior* (Leigh & Brandt, 1993).

4.2.3 Visual Display Systems

Currently the most popular laptop screen technology is the liquid crystal display (LCD). Commonly available active matrix LCDs have increased the contrast ratio to 50:1, increased response time, and have reduced ghosting from voltage overspill. They typically possess up to 1024x768 pixels in display sizes on the order of 30 to 35 cm (diagonal measurement). At the recommended viewing distance of 4 m (see Section 3.1.1), this results in a pixel size on the order of 0.2 minutes of visual angle. This is sufficient resolution for optotypes used in all measurements of visual acuity except "vernier acuity" (Boff & Lincoln, 1988, p. 199; NAS-NRC, 1980). That is, it allows for critical details of optotypes to be represented in laptop displays at nominal threshold and sub-threshold sizes required to assess the "frequency of seeing" over log steps in size (e.g., 0.75 minutes for Landolt Rings; NAS-NRC, 1980). At 4-m viewing distance, typical laptop displays allow for optotypes that subtend a vertical angle of up to 2.5 deg. This is sufficient for optotypes required to detect elevated thresholds comparable to a (metric) Snellen Fraction of 4/40 (NAS-NRC, 1980).

4.3 Measurement of Body Kinematics

4.3.1 Measurement of Eye Motion

As indicated in Section 3, explicit measurement of eye movements is not required for further development of the FVAT. At the same time, we recognize that information about the point of regard could be useful in some applications (e.g., research) or in future development of the FVAT. Suitable eye movement systems must be lightweight, unobtrusive, and permit full and unimpeded head and eye motion.

4.3.2 Measurement of Head Motion

Candidate technologies for the measurement of head motion include triaxial accelerometers and triaxial rate sensors. Both types of transducer have been used extensively in biomedical applications. Systems are available which are lightweight, reliable, accurate, and readily available. Cost is comparable for the two alternatives. There may be a preference in the use of linear vs. angular motion sensor.

One example of a solid-state angular rate sensor has a sensing mechanism consisting of piezoelectric bender elements mounted to a rigid base in a "tuning fork" configuration. The two drive elements are resonantly driven in opposite directions. When a rotation occurs, the momentum stored in the vibrating elements causes an out-of-plane bending force (called Coriolis force) which is demodulated to accurately depict the rotation rate. These solid-state angular rate sensors have no moving parts, no detectable hysteresis, and quick start-up, and are low cost since the sensors tend to be more electronic

than mechanical. The preferred configuration is a piezoelectric assembly that senses angular rates about its long axis.

Commercially available multi-axis accelerometers represent a state-of-the-art achievement in miniature design. One suitable example measures acceleration simultaneously in 3 perpendicular directions and offers an optimum combination of characteristics, which permit acceleration, vibration, and shock measurements where small size and mass are of prime importance. Resonant peaks are removed using 0.7 cr. nom. damping, thereby eliminating the fragility normally associated with miniature accelerometers, at the same time increasing the useful frequency to as high as 50% of resonance. They function in steady-state and dynamic measurement. Triaxials are mounted within a 12.7-mm cube with a nominal weight of 6g, and can be configured for a g-range of ±5g up to ±1000g. Power supply is 15v DC; linearity is ±1%.

4.3.3 Measurement of Postural Motion

An ideal system would provide pressure distribution measurement between soft and curved surfaces. One example of such a system consists of a flexible and elastic measuring mat, a multichannel analyzer, a calibration device, and a software package for personal computers. The measuring mats come in various sizes, sensor configurations and force ranges. The analyzers vary from small portable 16x16 sensor-matrix types to large 112x112 sensor matrix types with a wide range of options, such as master-slave synchronization of several systems, and dynamic amplification control. Because of the elasticity of the sensor mats they adapt perfectly to 3-dimensional deformations. The force transducing elements contain high-tech elastomers. Restoring force, range of force, threshold, hysteresis, temperature effect, frequency response, and other characteristics are determined during the manufacturing process. This makes it possible to adapt the sensor characteristic to the measuring problem. Together with the mat, the quality of electronic circuitry is also important. Particularly, the stability of the analog amplifiers, the type of signal conditioning, and the processing algorithms can dramatically influence the accuracy of the system. New analyzer technology allows individual calibration curves for each sensor, and also individual dynamic amplification control and crosstalk suppression, resulting in very accurate and reproducible pressure values.

4.4 Measurement of Light

Standard methods for measurement of luminance and contrast are described in Boff & Lincoln (1988) and NAS-NRC (1980). The following recommendations are based on those of the NAS-NRC (1980).

4.4.1 Measurement of Luminance

Luminance may be measured with a visual photometer like the Leed and Northrop MacBeth Illuminometer or the Schmidt-Haensch Beckstein photometer, which measure luminance directly in footlamberts and apostilbs, respectively. These can be converted to candles per square meter by multiplying the results by appropriate conversion factors (3.426 for footlamberts, 0.3183 for apostilbs).

A physical photometer like the Specta Pritchard photometer can be used in a similar way. The light entering the instrument must be filtered so that it is measured in photopic lumens. The luminance of the surround may be measured in the same way.

4.4.2 Measurement of Contrast

The axis of the photometer should coincide with the direction in which the display is viewed. In order to measure the luminance of the black letters and the adjacent white background, it is useful to convert the photometer to a microphotometer by placing a lens between the photometer and the display, which makes the peephole of the photometer conjugate to the display.

4.4.3 Measurement of Luminance Spectra

Commercially available spectrophotometers currently are available as PC plug-ins, and they are relatively inexpensive (e.g., several thousand dollars). However, measurement of the entire spectral distribution of the display or ambient luminance is not necessary. The "color" of the luminances can be obtained using the same devices described above in combination with three color filters placed, one at a time, between the photometric device and the display (or surround). The only requirement is that the spectral transmission of each filter is known. Such filters are commercially available and inexpensive.

5. Task 5 - Prioritization and Selection of Technology Solutions

5.1 Major Factors in Final Design Commitments

For the test to be robust, reliable, repeatable, and preferable, it must be easy to use and easy to understand. From prior experience of training operators to administer the locomotor DVA test, operator error must be addressed at each step in test administration, including: test & facility preparation (illumination, contrast, protocol sequence); instructions to subjects; performance scoring; archiving of data; and subject debrief. Where possible, assistance should be provided to the test operator by simplifying procedures, providing software-based wizards, and automating test administration and procedures (including data recording, archiving, etc.). Since the optometric test does not depend on familiarity with any alphabet, the test can be used internationally, and with nonreaders.

Increasing the diagnostic power and generality of the test results will significantly enhance the utility of the FVAT. This can be accomplished be establishing controllability over the various facets of the test (perturbation, illumination, etc.), and by ensuring commensurability with existing optometric tests and standards.

5.2 Recommended Design of the Functional Visual Assessment Test

A bundle of technology has been identified for integration into a system for functional assessment of visual acuity under conditions of whole-body perturbation. A preliminary design for the FVAT system has been completed. This proprietary design is the basis for proposals to support development of the hardware-software bundle.

6. Task 6—Plan for Continued FVAT Development

Proposals for continuing development of the FVAT system provide for extensive calibration and verification of the system both in the laboratory and in the field. Personnel and facilities at JSC and at the Baylor College of Medicine could be utilized in the empirical evaluation of the system while under development.

7. Research Issues

The primary objective of the initial R/R&D was to produce a feasible plan for the development of technology that would fulfill the needs of SMMaC for assessment of DVA in astronauts and integration of this FVAT with the Functional Neurological Assessment MER. It is important to note that the development of assessments with SMMaC, and interpretation of the results they provide, has been supported by cutting-edge research that has been conducted at JSC. The inclusion of a supplementary Task 7 in our initial work plan reflects the importance we see in the continuation of such cutting-edge research at JSC. In this section, we briefly consider questions about oculomotor and postural control that are especially well-suited to the unique capabilities the FVAT provides.

7.1 Compensatory Eye Movements

7.1.1 Objective of Compensation

A key area of research at JSC concerns eye movements that maintain a relatively stable point of regard in the presence of perturbations of the head movements. The intent to maintain a relatively stable point of regard (or direction of gaze) is exploited experimentally to assess the spatiotemporal characteristics of compensatory eye movements. The characteristics of compensatory eye movements, in turn, are often used to evaluate the sensitivity of various sensory systems to tilt/rotation of the head (i.e., the VOR), to bending of the neck (i.e., the cervico-ocular reflex), or to motion in the optic array (i.e., optokinetic nystagmus). This research makes explicit or implicit assumptions about the objective to minimize global change in the retinal image (e.g., "retinal slip"). Such assumptions do not imply that the objective is a conscious or even modifiable intention of an individual. They simply imply that the function of compensatory eye movements is to counteract the effects of head movements in order to achieve the objective of stable looking. At this level of description, such assumptions are generally uncontroversial.

At present, the precision with which eye movements can be measured and with which they can be evaluated with respect to perturbations of the head or optic array exceeds the precision with which the function of the eye movements can be objectively specified. We do not yet understand the degree to which eye movements must compensate for disturbances because we don't understand the costs and benefits of compensatory control as a function of the accuracy and precision of compensation and as a function of the spatiotemporal characteristics of the perturbation. In other words, we cannot specify the objective function for the oculomotor control system with much confidence about the quantitative details of this function.

7.1.2 Measuring Objective Consequences

The integrated FVAT facilitates research into the objective function for oculomotor control because it quantifies the consequences of perturbations to the head, in terms of effects on visual acuity, while it provides for precise experimental measurement and control of such perturbations. These consequences provide one objective basis for quantifying the costs and benefits of oculomotor compensation for perturbations. This is not to say that visual acuity is the only basis for objective control of the eyes. Visual acuity is, however, an uncontroversial and externally valid characteristic of visual perception. Thus, it would be enlightening to investigate the effects of head perturbations on visual acuity in a manner analogous to prior investigations of platform (e.g., vehicular) disturbances on visual acuity (see Section 2).

Prior research on vibration and display perception was directed towards improving the understanding of performance in vehicles. The FVAT allows this paradigm to be more directly relevant to human physiology by providing more control over perturbations of the body (e.g., of the head) along with precision measurement of these "inputs" to the postural and oculomotor systems. The relation between visual acuity, as an "output," and the postural inputs can be compared to the relation between eye movements, as outputs, and postural inputs. The FVAT reveals the former relationship. There is a considerable body of research on the latter. Thus, insight about the objective function for oculomotor control can be gained through research with the FVAT even without explicit measurement of eye movements.

Adding measurement of eye movements to research with the FVAT would be even more revealing. One then could test hypotheses formulated on the basis of comparisons between standard FVAT data and prior research on oculomotor control. One hypothesis worth investigating is whether there is a tolerance region in oculomotor compensation, that is, an amount of residual variation in the point of regard that is perceptually inconsequential. More generally, it would be interesting to evaluate the state space for such residual variation with respect to perceptual consequences such as visual acuity. This would reveal the timeliness and precision of compensatory eye movements required for well-specified levels of acuity.

7.2 Compensatory Postural Movements

Stabilization of the "platform" for the eyes is a fundamental assumption in our research on postural control (e.g., Riccio & Stoffregen, 1988, 1991; Riccio, 1993; Riccio et al., 1993; Riccio & McDonald, 1998) and in our collaborative research at JSC on posture and locomotion (McDonald et al., 1996a,b; McDonald et al., 1997a,b; McDonald et al, 1998). The FVAT provides the best apparatus to date for investigating this phenomenon. The modularity and flexibility of the FVAT allows it to be used in paradigms that are nearly identical to those that have been used in our collaborative research at JSC. At the same time, the FVAT can enhance the experimental control of postural perturbations and the relationship between perturbations and display presentations. It is worth considering some provocative modifications to prior methods that exploit this additional sophistication.

It would be interesting to assess the efficacy of postural control with respect to visual acuity under conditions of whole-body perturbation. Assessing this direct relationship requires constraints on the viewing situation that preclude the use of eye movements to compensate for the effects of whole-body perturbations on the optic array. One way to do this would be to have the observers wear goggles that

provide only a peephole through which to see the display. Perturbations of the head then could be objectively related to their consequences for visual acuity. This empirical relationship also would inform the research on eye movements outlined above (see Section 7.1) insofar as it would indicate the consequences of impaired acuity that compensatory eye movements presumably exist to minimize.

7.3 Coordination of Oculomotor and Postural Control Systems

The FVAT also can facilitate research into the coordination of eye movements and postural movements with respect to DVA. We have written several collaborative proposals for research to examine this coordination in the context of spaceflight, aging, and the relation between these two causes of sensorimotor impairments (e.g., Keshner, et al., 1995). The FVAT provides the best apparatus to date for conducting such research.

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13. ABSTRACT *(Maximum 200 words)*

Our theoretical and empirical research on the whole-body coordination during locomotion led to a Phase I SBIR grant from NASA JSC. The purpose of the SBIR grant was to design an innovative system for evaluating eye-head-trunk coordination during whole-body perturbations that are characterstic of locomotion. The approach we used to satisfy the Phase I objectives was based on a structured methodology for the development of human-systems technology. Accordingly the project was broken down into a number of tasks and subtasks. In sequence, the major tasks were (1) identify needs for functional assessment of visual acuity under conditions involving whole-body perturbation within the NASA Space Medical Monitoring and Countermeasures (SMMaC) program and in other related markets; (2) analyze the needs into the causes and symptoms of impaired visual acuity under conditions involving whole-body perturbation; (3) translate the analyzed needs into technology requirements for the Functional Visual Assessment Test (FVAT); (4) identify candidate technology solutions and implementations of FVAT; and (5) prioritize and select technology solutions. The work conducted in these tasks is described in this final volume of the series on Multimodal Perception and Multicriterion Control of Nested Systems. While prior volumes (I and II) in the series focus on theoretical foundations and novel data-analytic techniques, this volume addresses technology that is necessary for minimally intrusive data collection and near-real-time data analysis and display.

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